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Physiological Strain During Load Carrying: Effects of Mass and Type of Backpack

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Summary

The effects of mass (0, 5.4, 10.4 kg) and the type of support (on the shoulder or on waist) on physiological and mechanical strain indices of four young male subjects were quantified. While standing, oxygen uptake was not influenced by the type or mass of the backpack, and averaged 10% maximal oxygen uptake. The heart rate increased significantly by 9 beats per min while standing wearing a backpack. While walking (1.33 $m \cdot s^{-1}$) the mass significantly influenced both the heart rate and the oxygen uptake carried, but both types of strain remained below the tolerance limits for prolonged wear. Standing supporting a load did not significantly increase the EMG signal of the trapezius shoulder muscle (pars descenders). While walking, load carrying significantly increased the EMG of the shoulder muscles. The pressure on the skin under the shoulder straps during load carrying on the shoulders was more than a factor of three times higher than the threshold value for skin and tissue irritation. Load transfer to the waist with a flexible frame reduced the pressures on the skin of the shoulder to far below the threshold value. On basis of these results it was concluded that even with relatively low loads the limiting factor was the pressure on the skin, if a waist belt did not relieve such pressure on the shoulders.

Introduction

The main goal in most of the studies concerning backpacking has been to determine the energy cost of walking taking into account a variety of terrains (grade and surface), velocities, and external loads (Datta and Ramanathan 1971; Goldman and Iampietro 1962; Legg and Mahanty 1986; Myles and Saunders 1979; Pandolf et al. 1976, Pandolf et al. 1977, Pimental and Pandolf 1979, Soule et al. 1978) or to determine the level of metabolism, expressed as a percentage of maximal oxygen uptake (Vo_2max) which could be maintained without physical fatigue (Epstein et al. 1988; Shoenfield et al. 1977; Evans et al. 1980). A few studies have examined the effects of load-carrying on muscle activity (Cook and Neumann 1987; Bobet and Norman 1982), walking kinematics (Bloom and Woodhull-McNeal 1987; Martin and Nelson 1986), or the effects of load distribution on loss of mobility (Holewijn and Lotens 1992).

In this paper the effects of the mode of carrying and the load mass were investigated by simultaneous measurement of several physiological strain parameters. Firstly, from a study of the literature different types of strain were identified which could limit the endurance time of walking with a backpack (Holewijn 1986). It was found that besides a reduction in physical performance, effects on the metabolic, musculo-skeletal, and cardiovascular systems, and the skin underneath the shoulder straps are important. The aim of this study was to quantify all the resulting strains to assess the limiting factor in the endurance time of walking with a normally loaded backpack. It was hypothesized that local strain of the shoulder muscles or pressure on the skin under the shoulder straps could be the cause of frequent complaints during backpacking. Therefore, the load on the shoulder muscles was estimated with electromyographic techniques (EMG) and the pressure on the skin of the shoulder region was measured at several locations under the right shoulder strap to assess the distribution of pressure. The oxygen uptake (Vo_2) and the heart rate were also monitored to exclude the possibility that these strains were above the limits of tolerance.

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Methods

Subjects. Four healthy young male students participated in this study. They all participated regularly in physical activities but were not used to carrying backpacks. The subjects were informed of the purpose and procedures of the study and consented to participate. The subjects had a mean age of 24 years (range 23-26), mass of 75.1 kg (range 69-81.5) and Vo_2max of 3.4 $l \cdot min^{-1}$ (range 3.3-3.8).

Two packs were used in this study. One was the backpack in use in the Royal Netherlands Army (Mil), as pack mounted high on the back by straps. The straps ran from the front of the waist belt to the back being attached to the pack on the same side and crossing between the shoulder blades to reach the waist belt on the opposite side. On the shoulders the straps had a width of 5 cm and were of heavy canvas (Figure 1a). This type of backpack puts the load mainly on the shoulders. The second backpack was a custom-made pack (Cust) where most of the load was supported on the hips by means of a flexible frame connected to a padded 10-cm wide waist belt (Figure 1b). The padded shoulder straps were 8 cm wide on the shoulders.

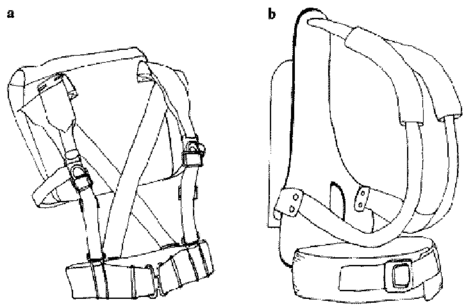

Figure 1. The two different types of backpacks used in this experiment. The small military backpack (a) hanging on the shoulders and the custom built pack (b) with a flexible frame, transferring the load on the hips.

Loads of 5.4 kg and 10.4 kg were chosen, representing the fighting and marching order of a Royal Netherlands Army soldier, respectively. These loads were applied both while standing and walking on a treadmill at a moderate walking speed of 1.33 $m \cdot s^{-1}$. Measurements without a pack served as control.

Physiological measurements and apparatus. The EMG activity of the descending part of the right trapezius muscle was measured with two surface silver-silver chloride electrodes (PPG, Hellige), positioned on the distal third of the muscle with an inter-electrode distance of 2 cm parallel to the muscle fibres. The electrodes were attached after thoroughly cleaning the skin with alcohol. The reference electrode was attached on the acromion. The EMG recordings started 1h after application of the electrodes because by that time the skin impedance had almost stabilised (Zipp et al. 1977).

The EMG signals were first passed through a small battery fed preamplifier (100x), mounted on a waist belt, and then through an amplifier with a gain of 2 x -50 x and a band filter of 5-1,000 Hz (slopes: low pass filter 6 dB $\cdot$ octave $^{-1}$; high pass filter 12 dB $\cdot$ octave^{-1}). The EMG was then sampled over 1 min periods by a microcomputer (IBM, USA) using a 12 bit A/D board (DT2821, Data Translation, USA) set at a sample frequency of 2,048 Hz, and stored on a hard disk. The root mean square value (RMS) of the amplitude was determined on line with a custom built (RMS) detector (AD 637, time constant = 55 ms) and sampled with the same equipment.

Post experimental analysis of the EMG consisted of dc-correction with a data analysis software package (Asystant, Macmillan Software Company, USA). From every EMG recording four samples of 1 s duration, equally distributed over the 1 min sample period were taken. The RMS data of these four samples were transformed to force values using a previously determined RMS versus force relationship. This calibration curve between RMS of the EMG of the trapezius muscle and the force produced by this muscle was determined for each subject with two adjustable slings running over the shoulders, one of which was connected to a floor mounted force transducer (Z 2H6, Hottinger Baldwin Messtechnik). The shoulder was positioned directly above the force transducer. The subject performed three isometric maximal voluntary contractions (MVC), with a 10 min rest period between each contraction, by lifting the shoulders, while sitting with a straight back and with the feet not touching the floor. This posture was chosen to ensure that the force could only be produced by lifting the shoulders and not by other means (leg muscles, leaning forward). The highest force level maintained for 3 s was taken as the MVC. After 30-min rest the RMS value was measured for 1 s at force levels of 5%, 10%, 20%, 30%, 50%, and 100% MVC. Between each measurement there was a 10-min rest. By power regression a curve was fitted to the data.

The pressure under the shoulder strap on the skin of the right shoulder was measured with a miniature pressure transducer (model 156, Precision Measurement Company, USA) measuring 8.5 x 4 mm and 1 mm thick. The small dimensions made it possible to measure the pressure with a minimal change to the curvature of the shoulder strap thereby introducing a negligible artifact in the recordings. The pressure signal was amplified (MG 3150, Hottinger Baldwin Messtechnik, FRG) and sampled by an IBM microcomputer with a sample frequency of 2,048 Hz and stored on disk. While the subjects were standing the pressure on the skin was measured at five positions under the right shoulder strap and for each position at three locations, i.e. the lateral and the medial edge of the strap and in the middle. The five positions were spaced out equally over the shoulder strap at intervals of 5 cm, position 3 being just on top of the shoulder. During walking the skin pressure was measured only at position 3 on the medial edge of the shoulder strap.

The Vo_2 ($l \cdot min^{-1}$) was measured with an Oxylog portable system (Morgan Ltd. England) which was mounted on a fixed frame above a treadmill. The Vo_2 ($l \cdot min^{-1}$) was normalised with respect to each subject's Vo_2max and with respect to the total load (mass of the subject + load). The Vo_2max was estimated during a submaximal treadmill running test, by increasing the running speed at 3% gradient until a heart rate of 160 beats$\cdot$ min^{-1} was reached. The Vo_2max was calculated by extrapolating the subject's heart rate versus Vo_2 relationship to his maximal estimated heart rate (Astrand and Rodahl 1986). This method had the advantage that the subjects were not stressed to their limits, but the accuracy was 10%-15% less than a direct measurement of Vo_2max (Davies 1968).

The heart rate was monitored continuously by a custom-built cardiotachometer with a charcoal electrode set (Respironics, USA) mounted on the chest.

Experimental procedure. Before the load-carrying sessions, each subject's Vo_2max was estimated, followed by the measurement of the force versus RMS calibration curve. After a rest period of 30 min the load carrying sessions started. Each carrying session consisted consecutively of 20-min standing, 10-min rest and 20-min walking on the treadmill at a velocity of 1.33 $m \cdot s^{-1}$.

While standing and walking the oxygen uptake and heart rate were recorded continuously on a chart recorder. Both while standing and walking the pressure, the EMG and the RMS were measured at the 1st, 10th, and 20th min. Off-line, the average EMG and RMS values were calculated for each 1-min measurement period. This cycle was repeated five times, with a 20-min rest between each cycle. The five carrying conditions (no backpack, Military and the Custom built backpacks, each with a 5.4 and 10.4 kg load) were administered according to a balanced design.

Statistics. The data were assessed by analysis of variance (ANOVA) with the Systat computer programme (Systat Inc. USA) after checking normality of the data (Kolmogorov-Smirnov test) and the homogeneity of variance. If significant F values were found ($P<0.05$) the differences between levels within an effect were analysed for significance by a Newman Keuls post hoc test ($P< 0.05$).

Results

Oxygen uptake

There were no significant differences found in metabolism of the 1st, 10th, and 20th min in any of the carrying sessions. Therefore, the data were averaged over the three measuring points. In Figure 2 the effect of the type of backpack on the relative metabolic strain is shown. During standing the metabolic strain was not significantly influenced by the load and averaged 340 ml · min^{-1} (10% Vo_2max). However, during walking differences between loads were evident. Compared to standing, walking with the 5.4-kg load caused a significant increase of the oxygen uptake of 620 ml · min^{-1} (1.5% Vo_2max) and with the 10.4 kg load the increase was 740 ml · min^{-1} (4.8% Vo_2max).

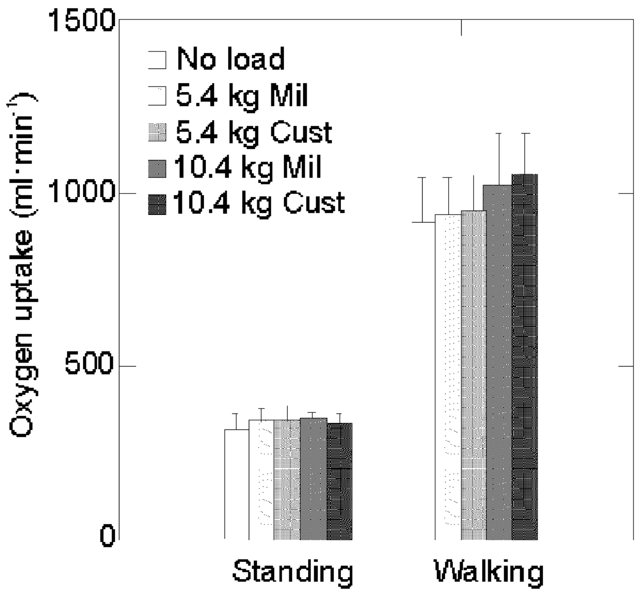

Figure 2. The effect of different combinations of load and backpack type on the metabolic strain (oxygen uptake, ml · min^{-1}), while standing and walking (speed = 1.33 m · s^{-1}). Mil, Military backpack; Cust, custom built backpack.

No significant difference was found between the two types of backpack. Comparing the oxygen uptake for the two different loads, the energy cost necessary for displacement of body mass and load separately can be calculated. The average energy cost during walking without a load amounted 4.2 W· kg^{-1} of body mass. However, the average energy cost per kg load at first decreased (1.1 W·kg^{-1} for the first 5.4 kg backpack mass) but then increased (6.3 W· kg^{-1} for the next 5 kg of backpack mass) with increasing loads. The average energy cost per kg load for the first 5 kg was thus lower than for a kg of body mass, but increased steeply with increasing loads.

Heart rate

During standing the average heart rate increased significantly by 9 beats· min^{-1} with load carrying. There was no significant difference between the four load carrying conditions (Figure 3). During walking the heart rates during control measurements remained significantly lower than the heart rates during the load-carrying conditions (Figure 3).

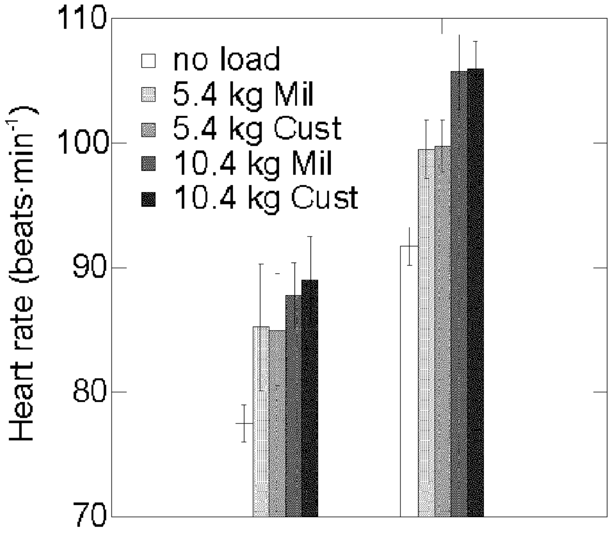

Figure 3. The effect of different combinations of load and backpack type on the heart rate (mean and SD) while standing and walking (speed=1.33 m·s^{-1}). Mil=Military backpack; Cust=custom-built backpack

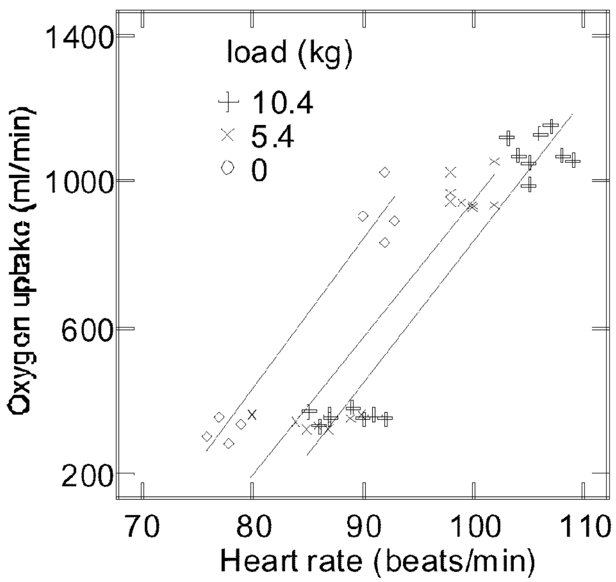

Figure 4. The effect of different loads on the relationship between the heart rate (beats · min^{-1}) and oxygen uptake (ml · min^{-1}) while standing and walking (speed=1.33 m·s^{-1}).

Electromyographic activity of the trapezius muscle amplitude

The statistical analysis revealed that there was no significant change in RMS over time. In further analyses the three measurements were averaged. Converting RMS values of the EMG of the trapezius muscle to force values resulted in the force levels shown in Figure 5.

Although the force level while standing showed an increase when they carried a load, the effect was not significant. The force averaged 5.4 N. While walking the force levels increased significantly during load carrying, but not in the control situation. The custom-built backpack with a 5.4 and 10.4 kg load and the

Military backpack with the 5.4 kg load resulted in similar force levels of 15 N (1.6% Maximal Voluntary Contraction, MVC), 17 N (1.7% MVC), and 19 N (1.9% MVC), respectively.

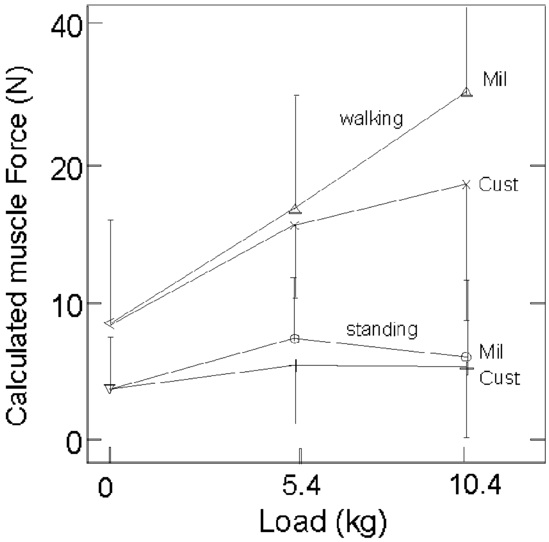

Figure 5. The calculated force level (N, mean and SD) of the descending part of the trapezius muscle while standing and walking without a load and using two types of backpack carrying 5.4- and 10.4 kg loads. Mil, Military backpack; Cust, custom built backpack

The Military backpack, however, containing a 10.4-kg load resulted in a force level of 25 N (2.7% MVC), which was significantly higher than in the other three load conditions. The force level was significantly dependent on the subject, in particular for the heavy load. This explains in part the variation in force level. With the Military backpack the increase in force, comparing standing and walking, was significantly higher than with Custom-built backpack.

Pressure of the shoulder straps on the skin

While standing the pressure distribution on the skin under the right shoulder strap measured in each of the 15 sites is graphically represented in Figure 6, showing the differences between the two backpacks and the effect of increasing the load. The two backpacks induced a pressure increasing from the back at the lower edge of the scapula to the top of the shoulder and a sharp decrease on the front side of the shoulder. Carrying the loads using the Military backpack caused a peak pressure on the acromion (top of the shoulder outerside) and another on the upper edge of trapezius muscle (top of the shoulder, innerside).

The former peak was also found using the Custom-built backpack, but smaller in amplitude. The peak pressure on the medial side was not present with Custom built backpack. The peak skin pressures using the Military backpack were significantly higher than the skin pressures using Custom-built version.
The maximal pressures amounted to 20 kPa (150 mm Hg) (Military backpack, 5.4 kg), 27 kPa (203 mm Hg) (Military backpack, 10.4 kg), 2 kPa (15 mm Hg) (Custom built backpack, 5.4 kg and 10.4 kg).

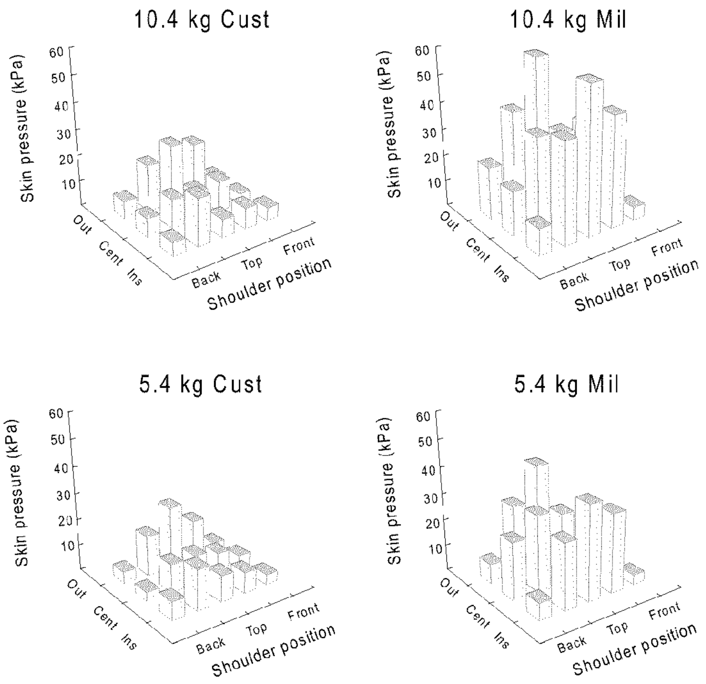

Figure 6. The distribution of average skin pressure of the right shoulder measured at five positions under the shoulder strap (from back to front side) while standing carrying two different loads and using two types of backpack. For each position the pressure was measured in the middle of the strap (cent) and at the inner side (Ins) and outside (Out.).

At most positions the pressure on the edges of the shoulder strap was higher than in the middle of the strap. The statistical analysis showed further that increasing the load from 5.4 to 10.4 kg in the Military backpack caused a significant increase in the skin pressure of 36%, whereas no significant effect was found with Custom-built versions. The form of the pressure distribution did not appear to be significantly influenced by the load level.

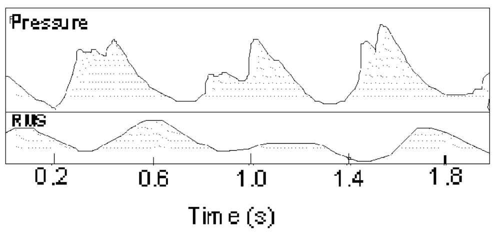

Figure 7. A typical example of the sinusoidal variations of the skin pressure and root mean square (RMS) of the electromyogram of the trapezius pars descendens muscle while walking (speed = 1.33 m $\cdot$ s^{-1}) using the military backpack with a load of 5.4 kg.

While walking the pressure showed sinusoidal fluctuations about 0.2 s out of phase with RMS of the EMG of the trapezius muscle (Figure 7). Similar to measurements made while standing, the skin pressure while walking was significantly dependent on mass and the type of backpack (Figure 8).

The Custom built backpack had a statistically significantly lower skin pressure on the top of the shoulder than the Military backpack. Further, the skin pressure using the Military backpack increased significantly with an increase in the load from 5.4 kg to 10.4 kg.

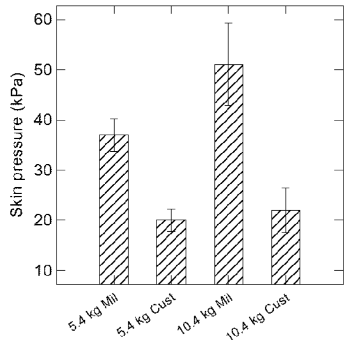

Figure 8. The skin pressure (mean ! SD) on the top of the shoulder while walking using two types of backpack and carrying two different loads. Mil, Military backpack; Cust, custom built backpack

Discussion

Metabolic and cardiovascular strain

In this study, in contrast to other studies, it was found that carrying a backpack had a significant effect on the heart rate while standing (Borghols et al. 1978; Pierrynowski et al. 1981; Pimental and Pandolf 1979). A possible explanation may be that in this study the time taken standing was more than a factor of two longer than in other studies and in combination with a different type of backpack this may have resulted in significant effects on the cardiovascular system. This increase in heart rate has been commonly observed during static muscular exercise. Kilbom (1976) has concluded in her review that the resulting increase in cardiac output during static contractions is mainly directed towards the peripheral parts of the body and only a small part is supplied to the myocardium. In this study standing while carrying a backpack, however, required no significant extra metabolic energy which is in agreement with other studies (Borghols et al. 1978; Pierrynowski et al. 1981). Thus, the relationship normally found between heart rate and the oxygen uptake during dynamic exercise was disrupted during static contractions, as can be seen in Figure 4 .

In most studies it has been assumed that the metabolic cost per kg load is independent of the total mass for loads carried centrally on the body (Goldman and Iampietro 1962; Datta et al. 1973; Myles and Saunders 1979; Pierrynowski et al. 1981; Pimental and Pandolf 1979; Soule et al. 1978). However, according to our data the average energy cost per kg added weight is not constant. During walking without a load the energy cost amounted 4.2 $W \cdot kg^{-1}$ of body mass. During weight carrying, the average energy cost per kg load at first decreased (1.1 $W \cdot kg^{-1}$ for the first 5.4 kg load) but then increased (6.3 $W \cdot kg^{-1}$ for the next 5 kg load) with increasing loads. The average energy cost per kg load for the first 5 kg was thus lower than for a kg of body mass, but increased with increasing loads. A reasonable explanation for this is yet lacking.

The oxygen uptakes ($ml \cdot min^{-1}$) found in this study during walking and standing with the different loads were well predicted (r=0.97) with an equation formulated earlier (Holewijn et al. 1992)(Figure 9).

$$Vo_2 = 4.1 \cdot body\ mass + 0.367 \cdot (body{+}load\ mass) \cdot v^2 + 2.017 \cdot shoe\ mass \cdot v^2 \quad (ml \cdot min^{-1})$$

with: *v: walking velocity* ($km \cdot h^{-1}$);
body, load, and shoe mass (kg)

This regression formula consists of three components. The first term represents the standing metabolic rate, the second term represents the oxygen uptake due to displacement of body mass and centrally placed trunk loads. The third term represents the additional, far higher oxygen uptake per kg shoe mass.

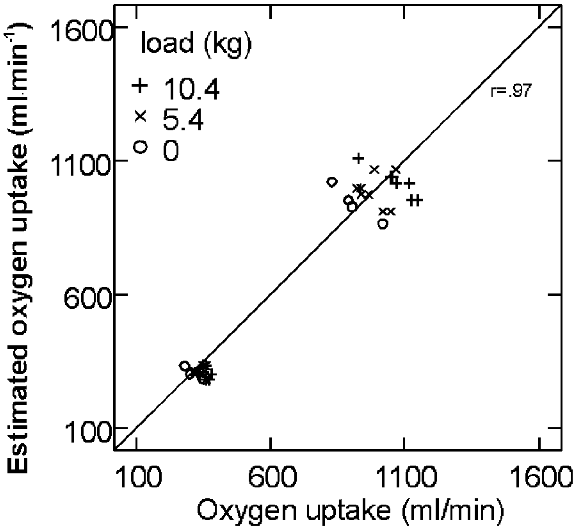

Figure 9. The relation between the measured oxygen uptake (ml·min^{-1}) and the predicted oxygen uptake (ml·min^{-1}) during standing and carrying a load of 0, 5.4 and 10.4 kg.

Several studies have shown that an oxygen uptake around 40% Vo_2 max and a heart rate around 110 beats·min^{-1}, can be maintained for periods of less than 2 h (Evans et al. 1980, 1983; Grandjean 1967; Michael et al. 1961; Nag et al. 1980; Nag and Sen 1979; Rutenfranz 1985). The measured metabolic and cardiovascular strains in the present study were below these levels so it may be concluded that for a young male population loads up to 10.4 kg would not limit the endurance time of walking. However, for a different age-group or sex these tolerance limits may be exceeded (Jorgensen 1985). Combining the data of the effect of age and sex on Vo_2max (Astrand and Rodahl 1986) with the energy prediction formula of Pandolf et al. (1977) one can estimate the external mass at which the metabolic tolerance limit is reached (Table 1).

Table 1. The estimated backpack load (kg) for men and women, at which the metabolic limit is reached at a walking speed of 1.33 m.s $^{-1}$ for three age-groups. It should be noted that this load is the sum of the mass of the backpack, and the mass of the clothing/equipment and the footwear.

Age (years)	External mass (kg)	
	Man	Woman
20	32	19
40	17	4
60	5	—

-: For a woman aged 60 years the metabolic tolerance limit is already exceeded without an external weight

It should be noted that these predictions are based on body masses of 60 and 70 kg for an average woman and man and a surface consisting of a flat hard top road. Other conditions will result in different predicted external loads. In particular, different terrains will increase the metabolic strain (Pandolf et al. 1976).

Muscular strain

Since Rohmert (1966) published the endurance curves for static contractions of the arm muscles, it has long been assumed that contractions below 15% MVC could be maintained indefinitely. The results of recent studies have shown that static contractions should be around 5% MVC to avoid the effects of fatigue after 1 h (Björkstèn and Jonsson 1977; Hagberg 1981; Jonsson 1978; Sjøgaard et al. 1986). In this study standing with the two loads resulted in average force levels for the descending part of the trapezius muscle well below 1%MVC. No differences existed between the two types of carrying system, although using the Military backpack most of the load was supported on the shoulders, in contrast to Cust. A possible explanation may be that while standing with a backpack the shoulder girdle is, for the major part, resting on the ribcage, needing only small muscle forces to stabilize the shoulder girdle and, therefore, no differences between the two backpacks should be found. However, walking with a load significantly increases the force level generated by the descending part of trapezius muscle, without surpassing the 5%MVC limit. It can be concluded that the force level generated by the descending part of the trapezius muscle during the carrying condition was below the static force level that can be maintained for a long period.

The cyclic variations in force while walking (Figure 7) can be explained from the kinematics of walking. According to Stokes et al. (1989) the pelvis rotates in the frontal plane opposite to the shoulder girdle during most of the stride cycle. The shoulder on the opposite side to the leg striking the ground is lifted and rotated forward. When this movement of the shoulder is impeded due to a load supported by the shoulder, the trapezius muscle has to generate a higher force to overcome this. From the data on the force generated by the descending part of the trapezius muscle during load carrying using the military backpack, it can be seen that with a load of 5.4 and 10.4 kg the extra absolute force level (above walking with no load) was 8.4 and 17 N per shoulder, respectively. The extra force generated by the descending part of the trapezius muscle doubled with a doubling of the load carried in the Military backpack . The force level during load carrying using the Custom built backpack was not significantly influenced by the load level, showing that most of the load had been transferred to the hips by the flexible frame, leaving on the shoulder only a constant load needed for stabilisation.

Skin pressure

According to Husain (1953), a skin pressure of more than 14 kPa (105 mm Hg) results in irritation, redness and, for an exposure time of 2 h, in subcutaneous oedema and inflammation of the dermis and underlying tissue. Besides the amount of pressure, the duration of the pressure is also an important factor in the development of the symptoms (Kosiak 1958; Stobbe 1975). Recently Sangeorzan et al. (1989) reported that for skin over muscle, a pressure of less than 10 kPa (75 mm Hg) reduces the transcutaneous partial pressure of oxygen, used as an index for local circulation, to zero. Therefore, it is assumed that in order to avoid these effects, the pressure applied on the skin under the shoulder straps should be below 10 kPa (75 mm Hg). The Military backpack exceeded this limit on the top of the shoulder for both loads. The Custom built backpack caused skin pressures far below this limit. High pressures can probably cause arm muscle weakness due to temporary failure of the superficial nerves in the plexus brachialis as found by Funaski (1978) and Rothner et al. (1975). As the skin pressure was the only strain clearly exceeding the tolerance limit, it is concluded that the frequent complaints during walking using the Military backpack, with relatively light loads, were caused by pressure on the skin under the shoulder straps. From the pressure measurements it can be seen that in the custom built backpack, the frame transferred a considerable part of the mass to the hips. This is not just displacing the problem to the waist, since the contact area between the waist belt and the hips can be quite large, by that reducing the pressure. The disadvantage is that to prevent the waist belt slipping off the hips it must be pulled tight, by that increasing the pressure on the skin. Data of Scribano et al. (1970) have shown, however, that the hips are less sensitive to pressure by a factor of three, so it may be concluded that load bearing by the hips is preferable to load carrying on the shoulders.

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